Laboratory Demonstration of Low Earth Orbit Inter-satellite Interferometric Ranging

R. Craig, J. Leitch, J. Howell, R. Pierce, T. Delker, M. Stephens
Ball Aerospace & Technologies Corp., PO Box 1062, Boulder, CO 80301

R.S. Nerem, P. Bender
University of Colorado, Boulder, CO 80309

I. Harris, B. Folkner
Jet Propulsion Laboratory, Pasadena, CA 91109

Abstract: We describe an interferometric inter-spacecraft ranging system with a demonstrated sensitivity of 1 nm/sqrt(Hz) level or better over frequencies of 10 to 100 mHz. We present our flight system concept and initial breadboard results.

I. Introduction

The advances made by The Gravity Recovery and Climate Experiment (GRACE) have led to an interest in launching a follow-on mission with even more ambitious scientific goals. Improved spatial resolution could be achieved through reducing the distance and ranging uncertainty between the two spacecraft, implementing a drag-free control system, and flying at a lower altitude. Such a mission, with improved ranging performance through the development of a n interferometric laser ranging system, has been proposed and would improve the spatial resolution by a factor of 5 for 1 cm water equivalent accuracy [1].

Our project goal is to prove the performance of a laser ranging system for the GRACE follow-on mission. We have developed a strawman flight design, an error budget, and have built a demonstration laboratory breadboard.

II. Measurement Concept

Our strawman design, like that proposed in [1], is a laser heterodyne interferometric ranging system. This is an active metrology scheme that uses two separate lasers, with the laser on one spacecraft phase-locked to the signal from the laser on the other spacecraft [2]. Fig. 1 shows the measurement concept and our strawman design for the optical bench on one spacecraft. The measurement is from proof-mass to proof-mass, so residual motions between the optical bench and proof mass that are not removed by the drag-free system do not affect the ranging signal.

Fig. 2 shows our concept for the optical bench on a single spacecraft. Light from the laser is coupled onto the optical bench via an optical fiber. A single refractive telescope is used to both transmit the light from the local spacecraft and

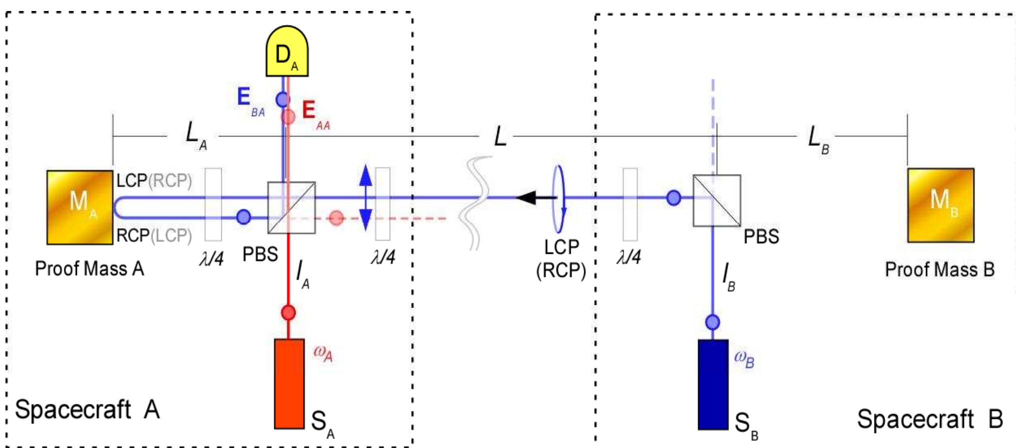

Fig. 1 The inter-satellite measurement concept for a GRACE follow-on mission. The laser on Spacecraft B is phase-locked to the laser on Spacecraft A. The beam path of the light received on Spacecraft B from Spacecraft A is not shown

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to receive light from the distant spacecraft. A spatial filter and bandpass filter are used to limit the effects of sunlight in the aperture on instrument performance. A quadrant photodiode at the output of the interferometer detects spacecraft pointing offsets through measurement of phase differences between the quadrants.

Important terms in the error budget shown in Fig. 3 include laser frequency noise, accelerometer noise, thermal effects, coupled wavefront distortion/pointing jitter effects, clock noise, and phase detection noise [3],[4]. The overall performance of a GRACE follow-on mission will be limited at low frequencies by the accelerometer noise and at higher frequencies by the laser frequency noise [1]. Control of those noise sources is not included in this effort. Our project goal is to ensure that all other ranging error sources related to the optical interferometry are less than the expected noise from the laser and the accelerometer.

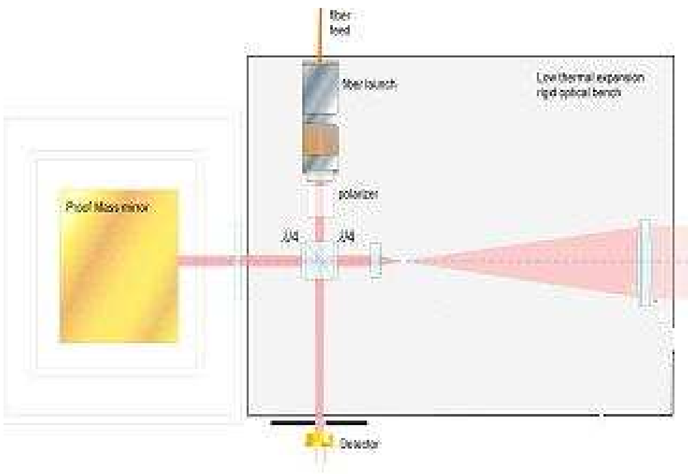

Fig. 2. Example of single optical bench for interferometric range transceiver.

III. Description of Laboratory Breadboard Ranging System

We have built a laboratory breadboard (Fig. 4) of the interferometric range transceiver (IRT), composed of commercially available parts. In addition to the interferometric measurement of length changes between simulated proof masses, the breadboard will demonstrate the integrity of the spacecraft pointing signal and demonstrate phase detection in the presence of Doppler shifts.

A. Breadboard Description

Two Lightwave Electronics 1.064 mm lasers are to be phase-locked together to form a coherent optical transponder [2]. Two flat mirrors are used to simulate the proof masses that would be part of the drag-free mission. Commercial beamsplitters, neutral density filters, and waveplates are used. A BlackJack phasemeter or a commercial high-speed digital lock-in amplifier measure the phase output of the photodetectors at a specified beat frequency set by the frequency offset of the phase lock between the two lasers. Simulated Doppler shifts can be introduced into the system through the laser phase lock electronics. Additional optical elements can be introduced between the two beam splitters in order to attenuate the beam or simulate pointing misalignment between the spacecraft.

B. Fabry-Perot Length Monitor

A Fabry-Perot (FP) cavity was used to monitor pathlength changes in the breadboard in hopes that this could be used to remove environmental disturbances from the ambient environment. The cavity end mirrors were positioned immediately above the mirrors representing the proof masses, and a portion of the master laser light was used to servo the master laser frequency based on the error signal derived from the FP cavity. The residual error from the closed loop control of the laser frequency was below the 1 nm/sqrt(Hz) goal of the IRT interferometer measurement.

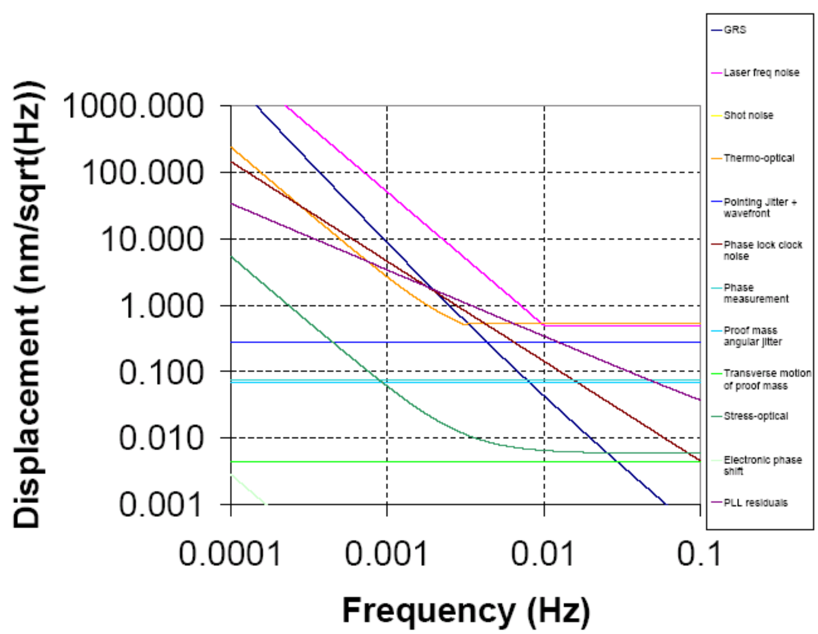

Fig. 3. Error budget based on flight concept guides laboratory demonstration.

C. Pointing description

Measurements of the pointing offset of the laser beam from the distant spacecraft are made at the interferometer output port by a quad cell phase detector. The phase measurement in the four quadrants is made separately using different channels on the BlackJack phasemeter. The average of the phase measurements gives the science measurement of the overall fringe phase between the signal arriving from the other spacecraft and the local laser. The normalized difference between the fringe phases measured in opposing quadrants gives a beam pointing offset between the local beam and the one received from the other spacecraft.

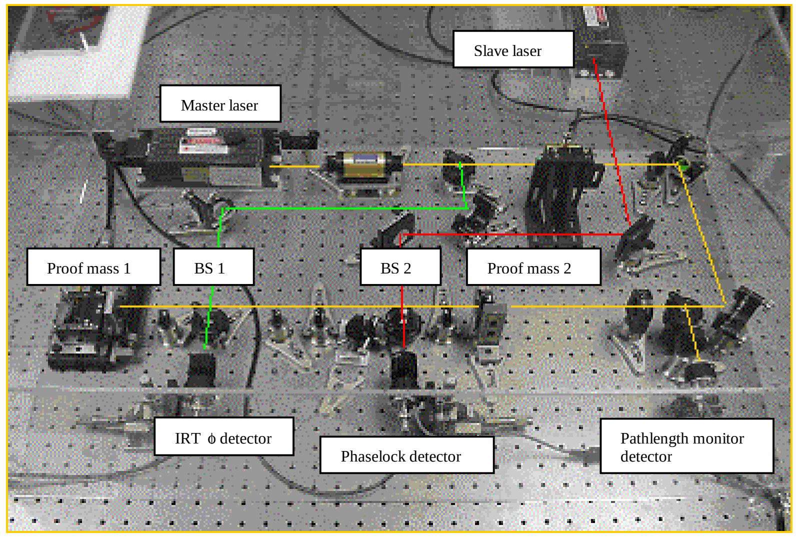

Fig. 4. Breadboard realization of interferometric range transceiver.

IV. Performance of the Laboratory Breadboard Ranging System

Tests to date consist of breadboard measurements made first in ambient air followed later by space-like vacuum conditions. In ambient air, while the locking characteristics of the FP servo were good, it was not effective in removing effects of local turbulence from the measurement of length changes between the proof mass mirrors. Data of Fig. 5 were recorded with and without the FP servo disabled; measurements made of interferometer performance in air under a plexiglass box showed sufficient stability to demonstrate the breadboard operation.

The locking of the second laser to the phase of the first laser gave reasonable results for the ambient conditions. The two curves show performance with (upper) and without the FP servo enabled. The performance without the FP servo shows a phase-locking performance that is above allocated levels, but may still be limited by ambient effects of air currents and vibrations.

The goal of vacuum measurements was simply the removal of air turbulence effects and validation of system baseline performance. The breadboard configuration was moved to a small optical bench of sufficient size to duplicate the arrangement of Fig. 4 but fit inside the small vacuum chamber shown in Fig. 6. The chamber is cylindrical with six feedthrough ports for optical fiber, electrical connections and vacuum. The end doors are acrylic and permit easy observation during pump-down and operation. The system operates at 5 – 25 Pa pressure with the aid of a dry rotary pump. The breadboard is mounted on steel rails for easy setup and alignment outside the chamber.

The initial configuration shown in Fig. 6 placed both laser sources outside the chamber with light conducted inside via polarization maintaining (PM) optical fiber. However, it was quickly learned that we had not adequately accounted for spurious interferometer paths that required a more careful layout. The decision was made to place the lasers temporarily inside the vacuum chamber to establish system performance in vacuum while a revised optical fiber layout was devised. This arrangement imposed a modest thermal load on the breadboard causing expansion. In this case, the FP path monitor proved to be invaluable at compensating for the induced drift. The data recorded with this approach is shown in Fig. 7.

The figure on the left represents the performance of the

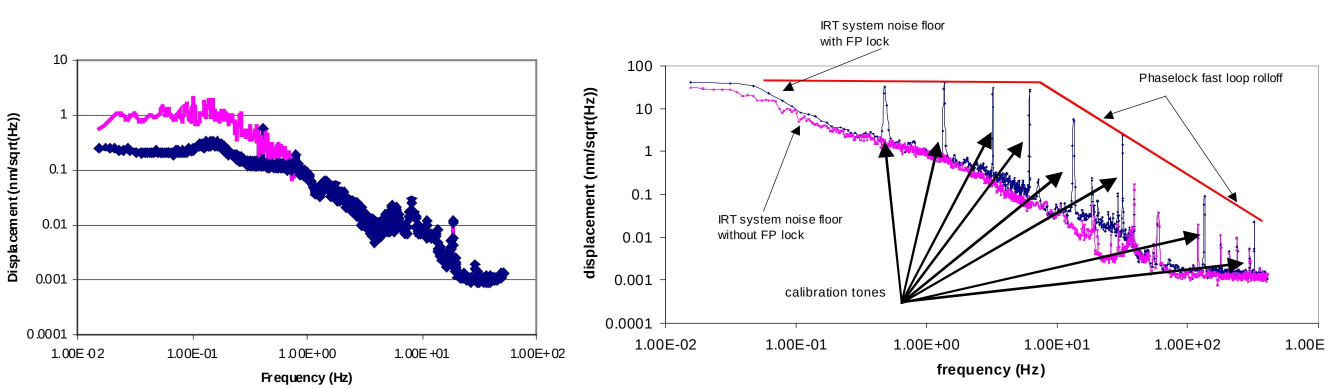

Fig. 5. Phase-locked loop performance (left) and IRT performance (right) with (top) and without (bottom) FP servo activated. Performance in air is limited to 10’s of nm/sqrt(Hz).

system at frequencies below 1.5 Hz for both the phase-locked loop and the IRT signal. For frequencies above 30 mHz, the performance is virtually identical indicating effective elimination of the limitations imposed by air. The target of sensitivity of 1 nm/sqrt(Hz) was easily achieved. The divergence below 30 mHz is not yet fully understood but is likely due to residual uncontrolled thermal noise. The figure on the right represents the performance of the system with the FP servo again disabled for the purpose of system calibration. An 800 mHz tone is shown being imposed on the master laser to simulate pathlength displacement. In this case, thermal drift forces low frequency sensitivity to rise above 10 nm/sqrt(Hz). Until we successfully replicate this performance with our optical fiber sources, the question of whether the FP pathlength monitor is necessary on the brassboard remains open.

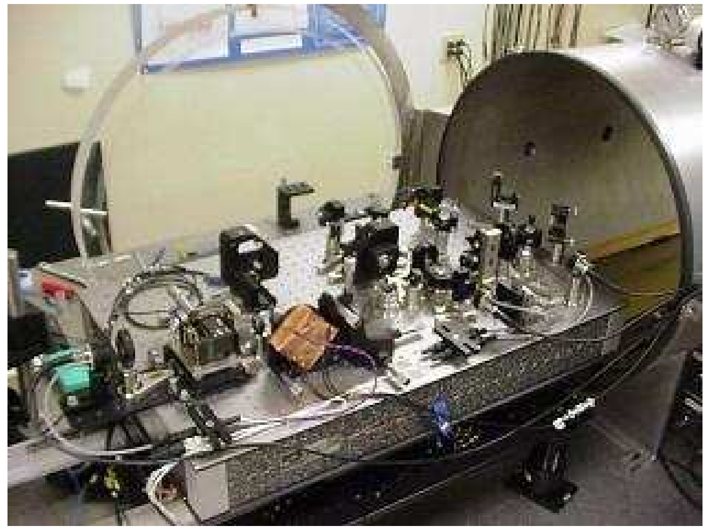

Fig. 6. Breadboard layout prior to operation in vacuum.

V. CONCLUSIONS

An interferometric range transceiver is a key component to a GRACE follow-on mission with enhanced spatial resolution in the measurement of the Earth's time-varying gravitational field. We are working to advance the technology of interferometric ranging in low Earth orbit. An error budget based on a simple design for a heterodyne interferometer has guided the development of a laboratory breadboard that will validate our error budget and pointing scheme. Initial measurements with the laboratory breadboard indicate that air currents, despite the inclusion of an independent path monitor, limit the performance. Inclusion into a vacuum system has largely validated this, demonstrating the effectiveness of the path monitor. Future work will include subjecting a flight-like brassboard to testing in relevant space-like environments.

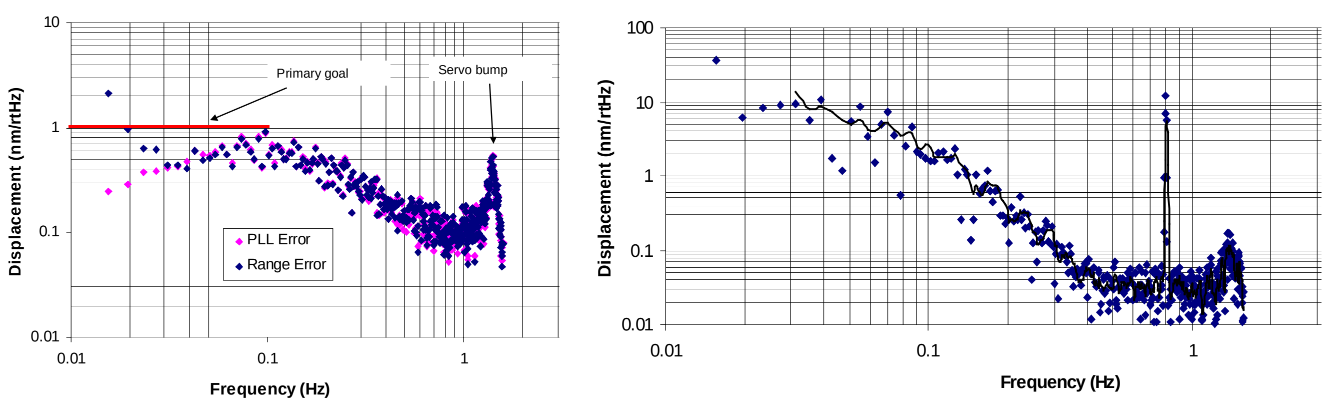

Fig. 7. Phase-locked loop compared to IRT performance in vacuum (left). IRT performance with lasers in vacuum without FP servo activated (right) with 800 mHz calibration tone. Performance with lasers in vacuum is limited without FP servo.

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